UCRL-CONF-204344

The Physics of Fusion Energy: Why We (Probably) Can't Make a Reactor on the Head of a Pin

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May 25, 2004

Innovative Confinement Concepts Workshop 2004
Madison, WI, United States
May 25, 2004 through May 28, 2004

Disclaimer

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Invited Tutorial Talk

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May 27, 2004

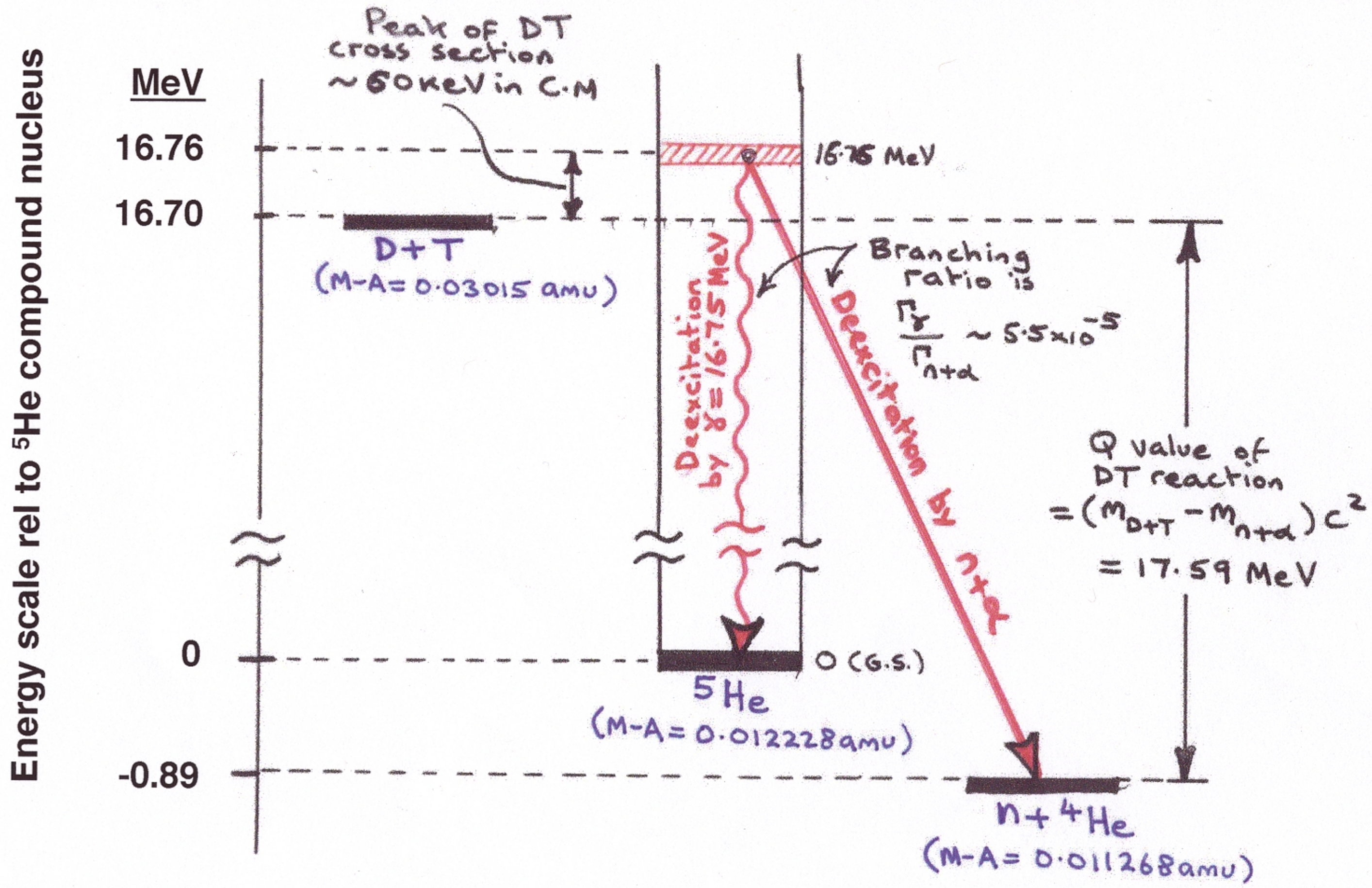
This work was performed under the auspices of the U.S. Dept. of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48

Some Candidate Fusion Fuels

Reaction		Products	Energy	$\langle\sigma.V\rangle$ at: 20keV	$\langle\sigma.V\rangle$ at: 200keV
Conventional (and it's still hard!):					
$D + T$	$\rightarrow$	$n + {}^4He$	+ 17.6Mev	4.2	6.3
Advanced fuels:					
$D + D$	$\rightarrow$	$n + {}^3He$	+ 3.3Mev	0.0052	0.88
		$p + T$	+ 4.0Mev		
$D + {}^3He$	$\rightarrow$	$p + {}^4He$	+ 18.4Mev	0.0038	2.4
You'll also get:					
$T + T$	$\rightarrow$	$n + n + {}^4He$	+ 11.3Mev	0.0025	0.42
${}^3He + {}^3He$	$\rightarrow$	$p + p + {}^4He$	+ 12.9Mev	0.0001	0.03
$T + {}^3He$	$\rightarrow$	$n + p + {}^4He$	+ 12.1Mev	0.003	0.92
$n + X$ (important for high ρ–R ICF targets)					
And if you think this is too easy….:					
$p + {}^{11}B$	$\rightarrow$	${}^4He + {}^4He + {}^4He$	+ 8.7Mev	0.0008	2.4
$p + {}^7Li$	$\rightarrow$	${}^4He + {}^4He$	+ 17.3Mev	comparable	
$p + {}^9Be$	$\rightarrow$	${}^4He + {}^6Li$	+ 2.1Mev	comparable	

Nuclear Energetics of the D-T Reaction

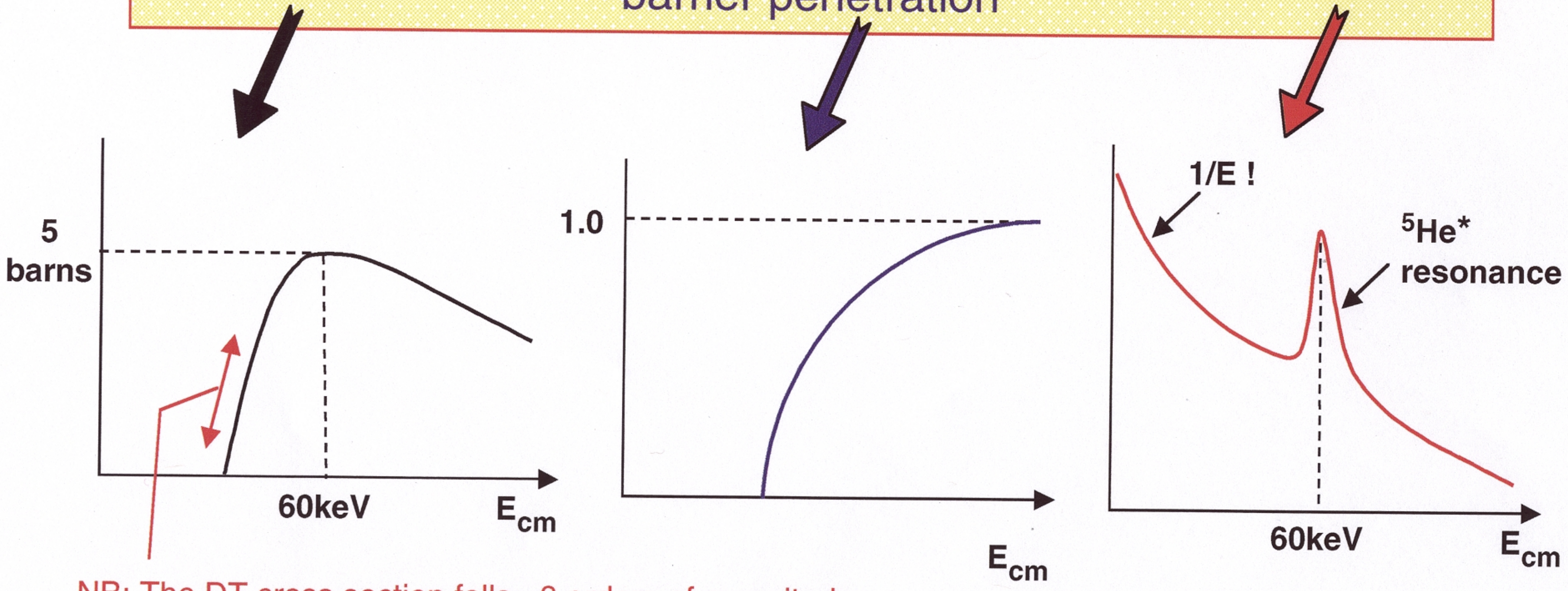
$D + T \rightarrow {}^5He^* \rightarrow n + {}^4He$



The Fusion Cross Section – and the Economics of (Thermonuclear) Fusion Energy – is Dominated by the Coulomb Barrier

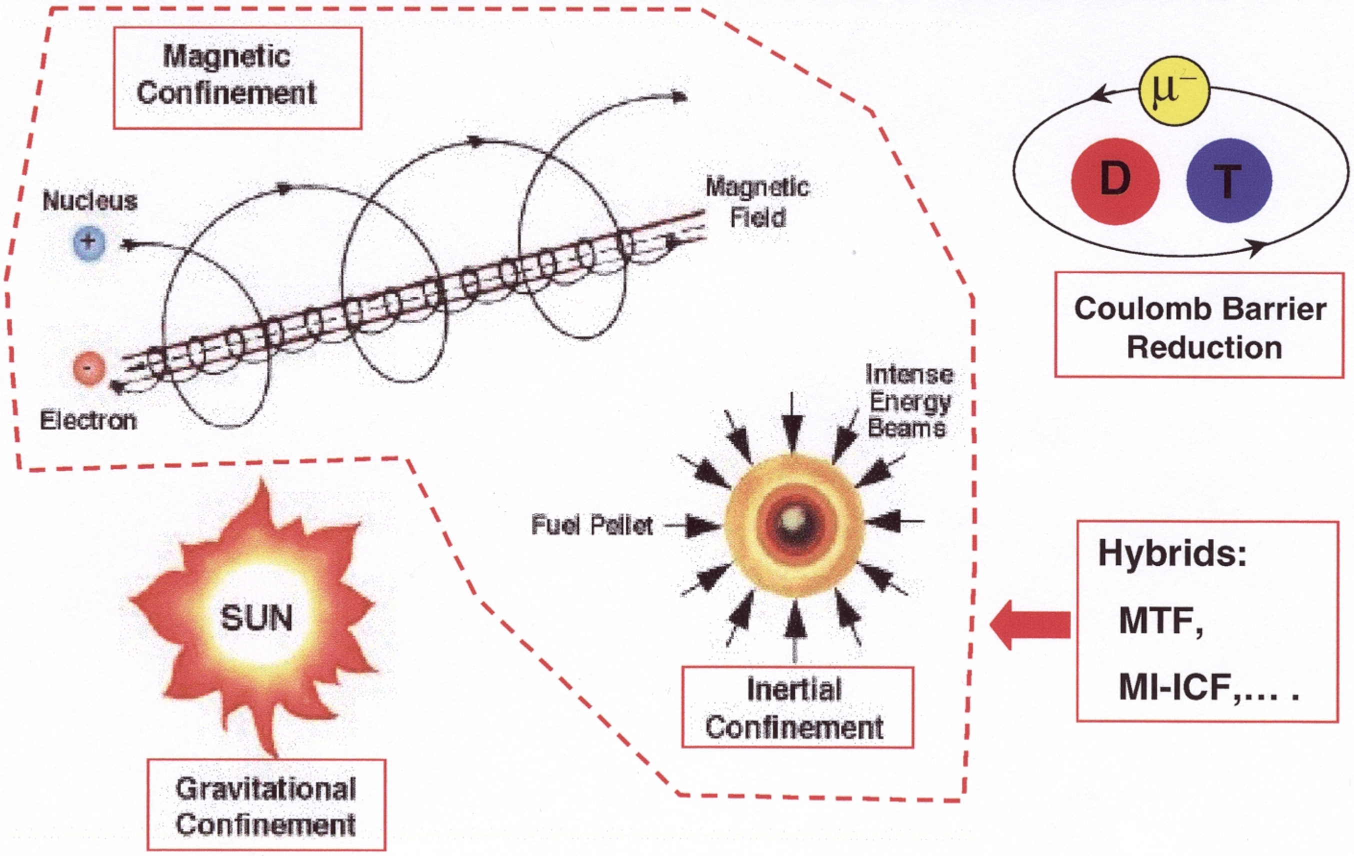
$$D + T \rightarrow {}^5He^* \rightarrow n + {}^4He$$

$\sigma(E_{cm})$ = prob of Coulomb barrier penetration × nuclear part



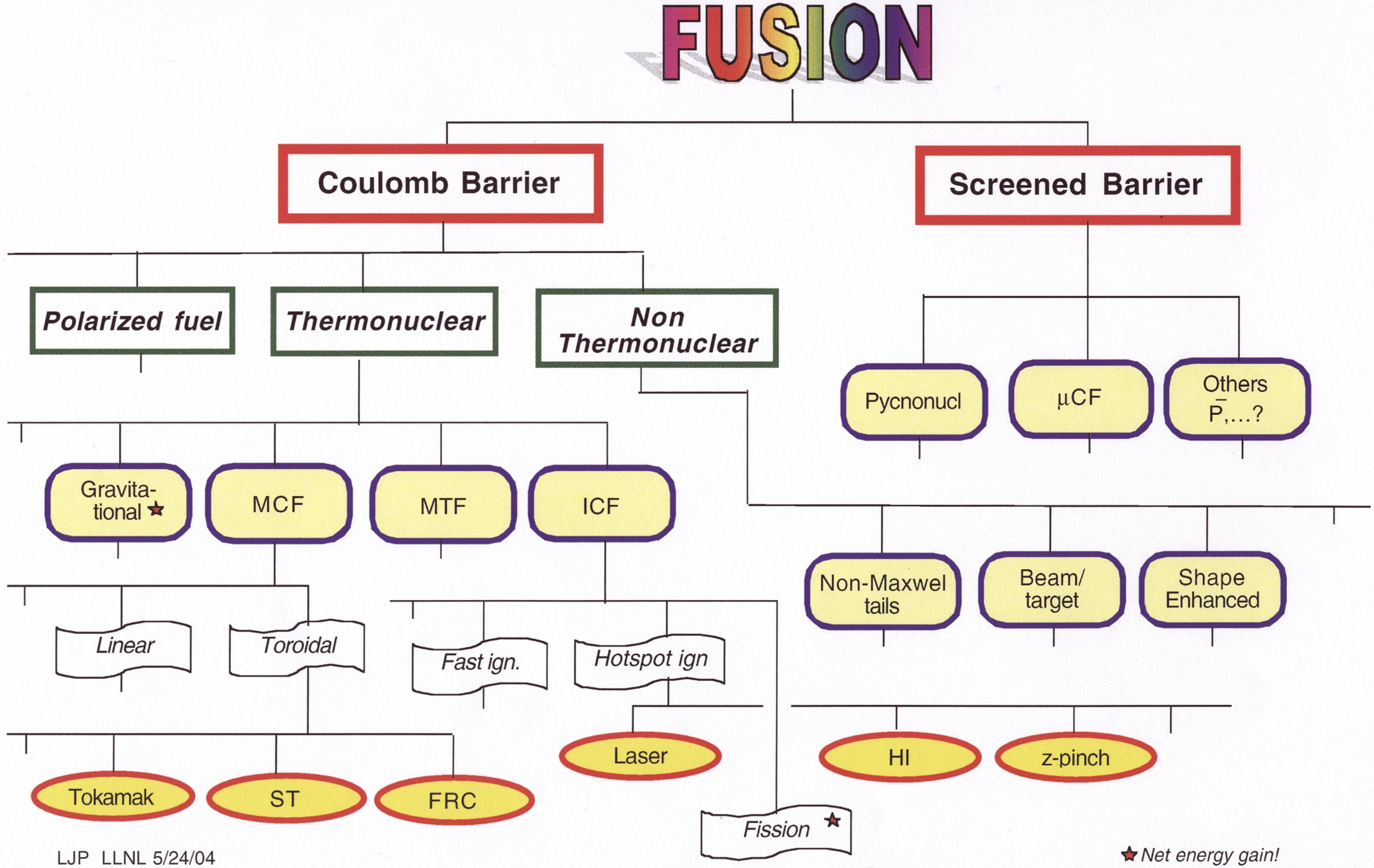
NB: The DT cross section falls ~8 orders of magnitude as energy is reduced from 10keV to 1keV!

There are Three (and Maybe More...) Ways to Achieve Fusion



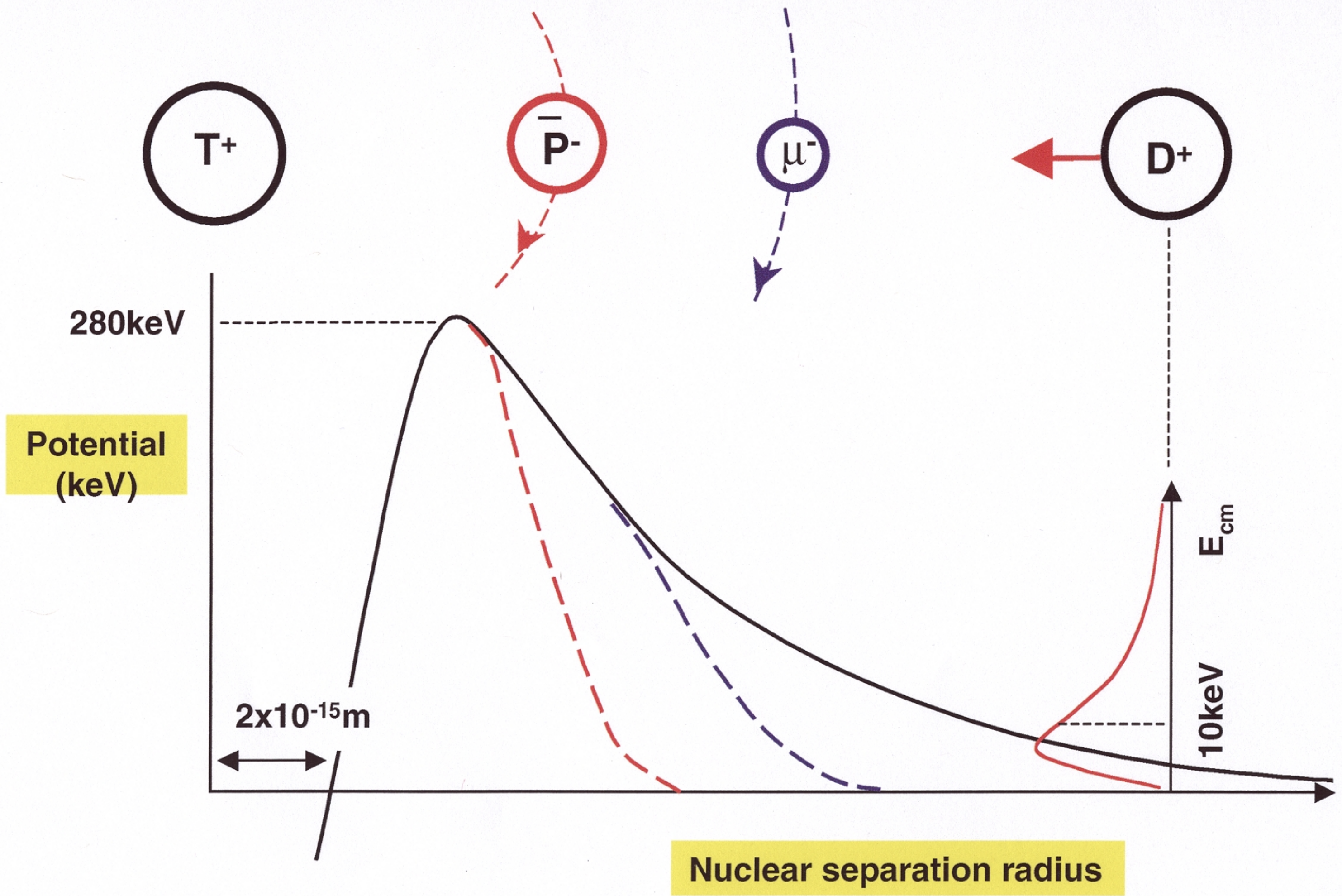
	Density	Temperature	Confinement Time
Magnetic	solid/10^8	10keV	seconds
Inertial	$10^3\times$solid	10keV (t=0)	10's picoseconds
Gravitational	$10^4\times$solid	1keV	10^5 years
Coulomb Barrier Reduction	solid	100's °C	Not applicable

How (⇒ net energy gain) ?

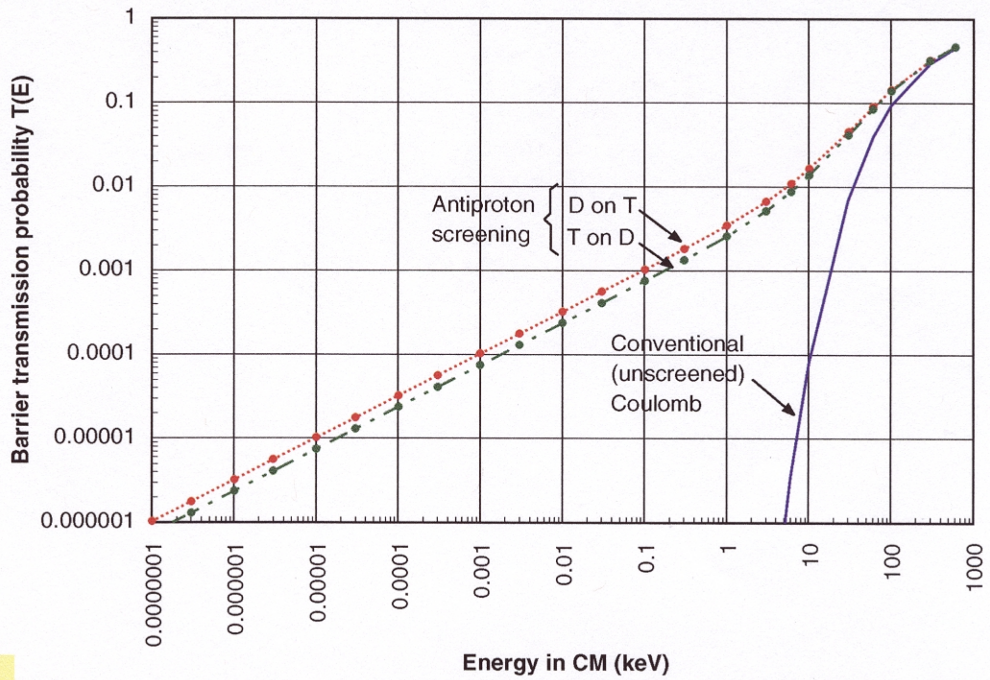


★ Net energy gain!

The Fusion Cross Section is Dominated by Coulomb Barrier Penetration

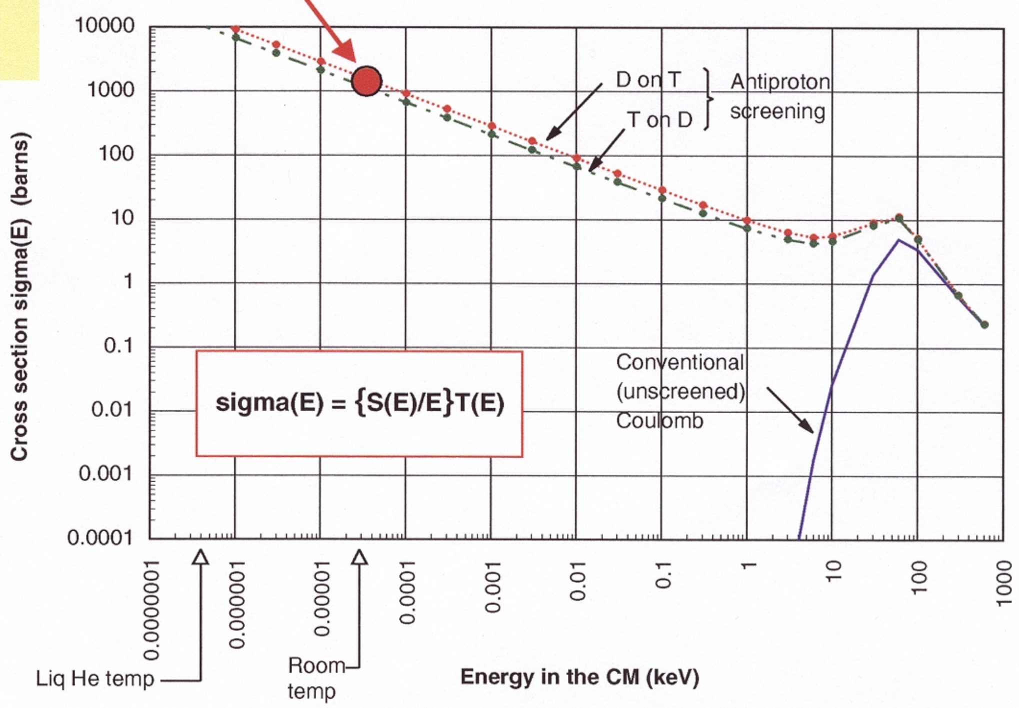


Modifying the Coulomb Barrier has a Dramatic Effect on Fusion Cross Section



DT FUSION REACTION: BARRIER TRANSMISSION PROBABILITIES FOR CONVENTIONAL (UNSCREENED) COULOMB POTENTIAL AND ANTIPROTON SCREENING

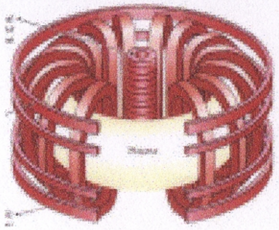
DT fusion cross section at room temperature is ~1000b! (twice the 235U fission cross section)



DT FUSION REACTION: CROSS SECTION INCREASE VIA ANTIPROTON SCREENING. THE 1/E TERM DOMINATES THE TRANSMISSION PROBABILITY AT LOW ENERGY

The Modus Operandi of Magnetic Fusion (Physics) Research

- Find a magnetic topology that holds a plasma in equilibrium



$\nabla p = j \times B$

- That is stable at desired operating pressures

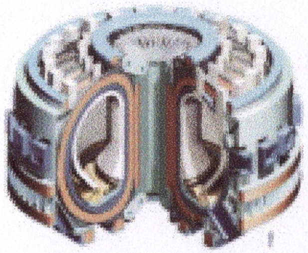
$\beta = 2\mu_0 p/B^2 \sim \beta_N I/aB, \quad q \sim a^2B/RI, \ldots.$

- That contains heat for a sufficient time to produce net energy gain

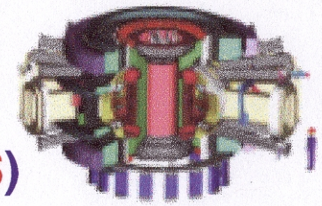
$P_\alpha + P_{aux} = E_{th}/\tau_E + P_{rad}, \quad Q = P_{fus}/P_{aux} \geq 10\ (20)$

$\Rightarrow n\,\tau_E T \sim \text{few} \times 10^{15}\ \mathrm{cm^{-3}s^{-1}keV}$

- For a sufficient burn time



ITER(~400s $$$$$)



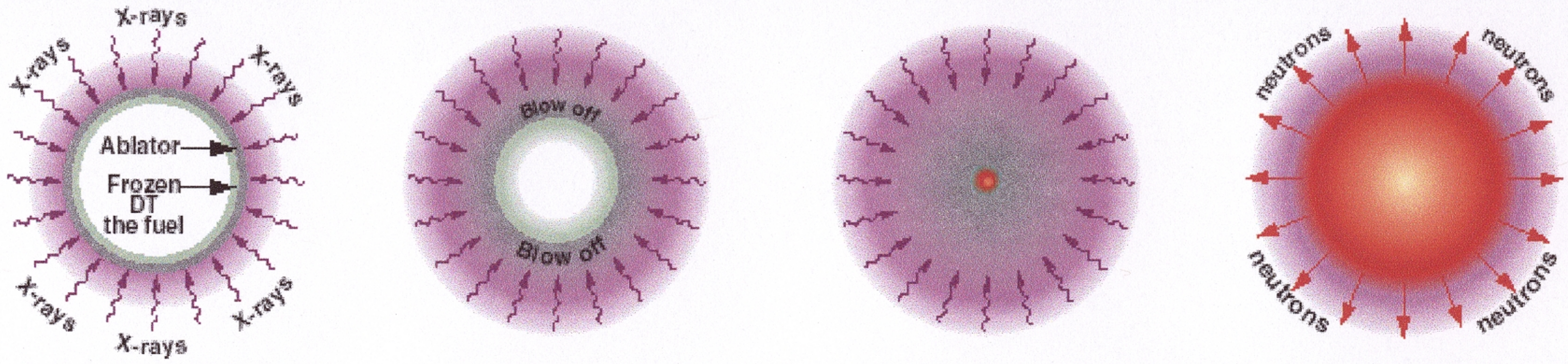
FIRE (~10s, $$)

- But, in any event:

$T \geq 100{,}000{,}000°C$

and losses scale as $\sim T,\ T^2,\ T^{1/2},\ \nabla T \ldots$

The Modus Operandi of Inertial Confinement Fusion (Physics) Research



X-rays or driver beams heat ablator

Rocket reaction implodes fuel shell

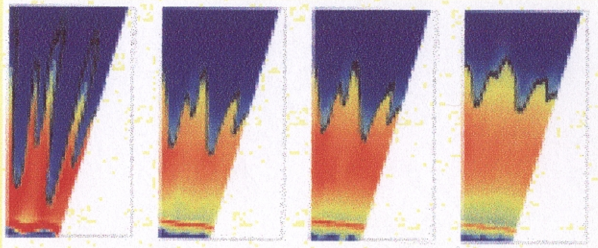
Fuel shell stagnates. Ignition begins in central hotspot

Burn propagates to compressed outer fuel Yield is produced

- **Ignition and propagating burn:**
  $(\rho R.T)_{hotspot}$ ~$0.3 g.cm^{-2}.10 keV$
- **Yield and gain:**
  $(\rho R)_{cold\ fuel}$ ~$3 g.cm^{-2}$
- **Why we need compression:**

If $\rho=0.25 g.cm^{-3}$, m=2.5kg, Y~70kt, E_{driver}~3GJ

If $\rho=400 g.cm^{-3}$, m=5mg, Y~500MJ, E_{driver}~1MJ



But it's all about the symmetry and stability!

Technology (and Humanity's) Constraints

- $Q_{eng} = P_{elec} / P_{recirc} = \eta_{th} P_{fus} / (P_{aux}/\eta_{aux}) = \eta_{th}\eta_{aux} Q \geq 3$ (at least!)

MFE: $\eta_{th}\eta_{aux} Q \geq 3$; $\eta_{th} \sim 0.3$, $\eta_{aux} \sim 0.5$; $\Rightarrow Q \geq 20$

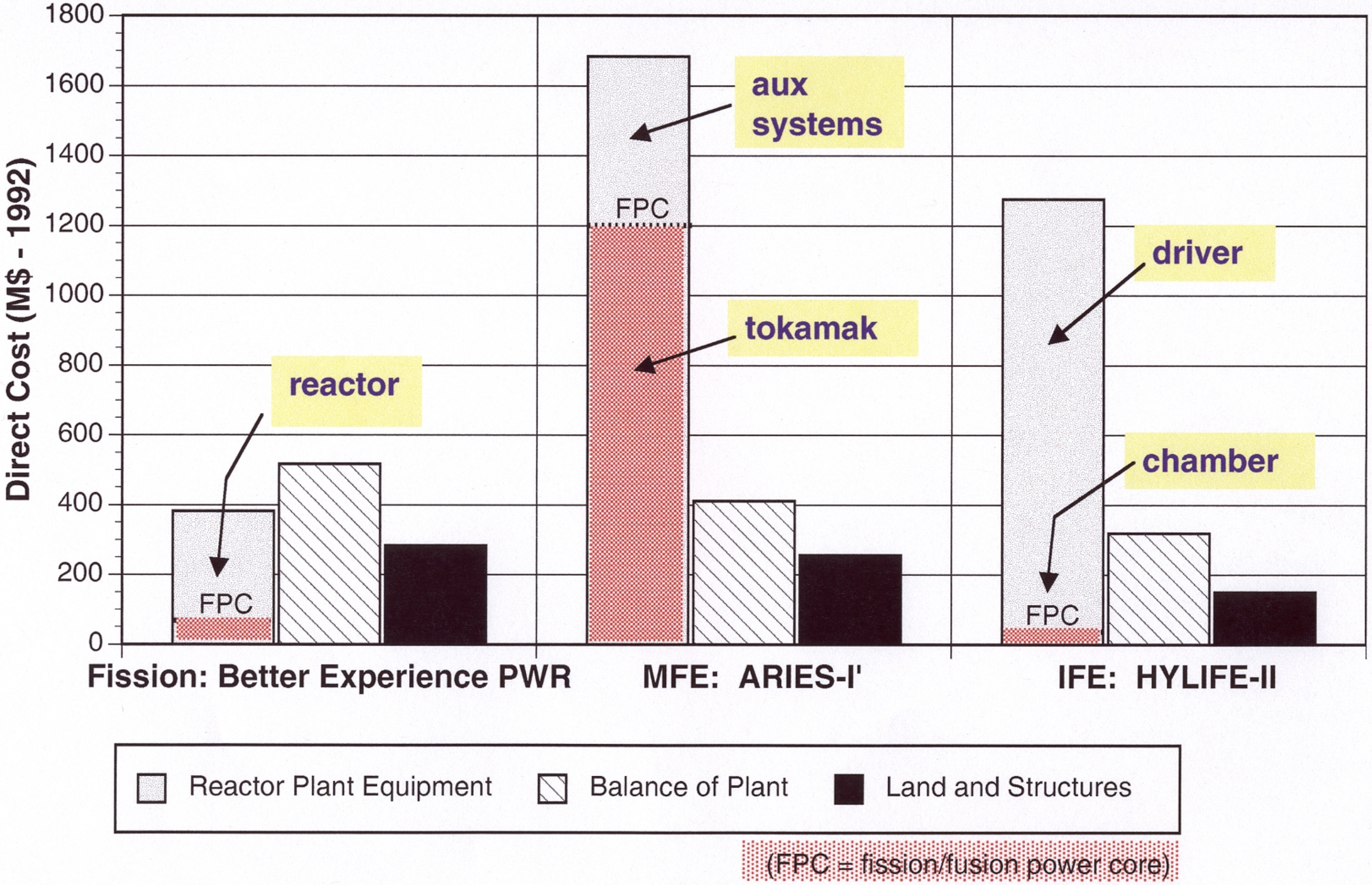
IFE: $\eta_{th}\eta_{driver} G \geq 3$; $\eta_{th} \sim 0.3$, $\eta_{driver} \sim 0.1$; $\Rightarrow G \geq 100$

Technology	
Shielding (nuclear cross sections)	⇒ Radial builds, materials
Surface heat flux; volumetric heat removal	⇒ Fusion power density, geometry, radial builds
Radiation damage	⇒ Radial builds, materials
Stresses	⇒ Magnet radial builds
Space charge, optics damage, beam access	⇒ Driver power densities, pulse compression,
Pulsed fatigue	⇒ Radial builds, materials, quality control

"Economics"	
Size / mass / cost	⇒ "Power density" of MFE core or IFE driver
Complexity	⇒ No. of systems, reliability, maintainability
Safety	⇒ Fusion power density, material choices, complexity
Environment (waste disposal)	⇒ Material choices, complexity
Proliferation	⇒ Fuel cycle, materials

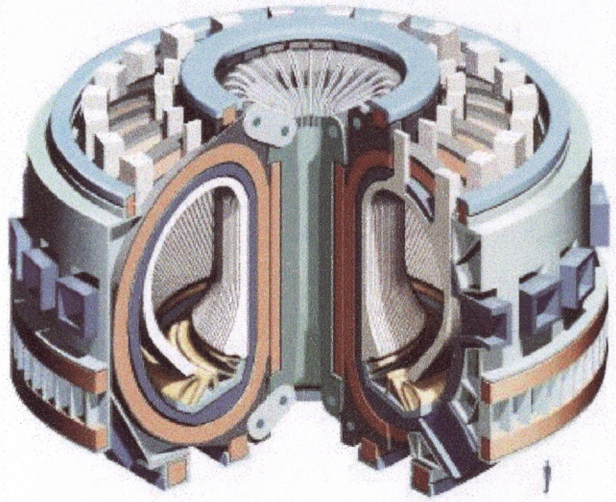
NB: ICF is doing it once; IFE is doing it ten times a second for 30-y at 90% availability!

Capital Costs: Fission -v- Fusion



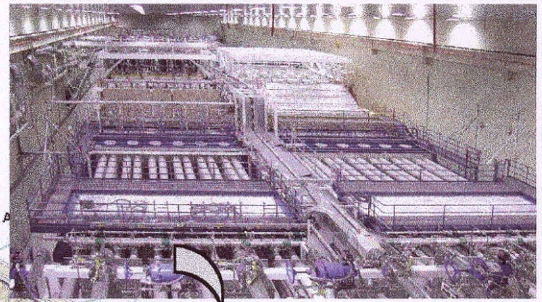
- ⇒ For MFE, the cost and complexity is in the fusion power core
- ⇒ For IFE, the cost and complexity is in the driver

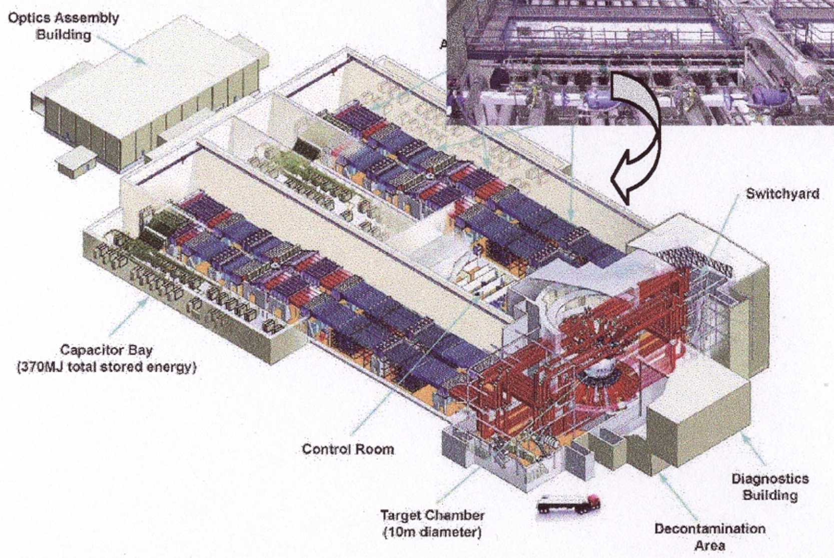
Present Fusion Systems are Very Complex (But, hey -- we're just trying to make it work at all !)



- ITER - 400secs

- NIF - 3 times a day

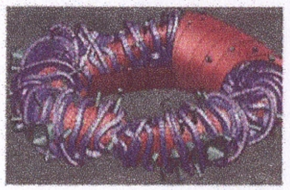




	Fission (ALWR)	Fusion (ARIES-RS)
Fuel power density (MW/m^3)	250	5
Fuel power flux (MW/m^2)	0.5	5
Fast neutron power flux (MW/m^2)	0.01 (2MeV)	4 (14MeV)
Core power density (MW/m^3)	10	1
Core mass (tonne)	500	8,000
Mass power density (kW_e/tonne)	1000	100
Rel. no. of pipes, welds, pumps, valves....	1	~10

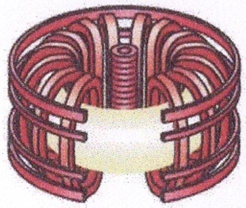
MFE: Reduce the Size, Cost and Complexity of the Fusion Power Core (Duh!)

Stellarator



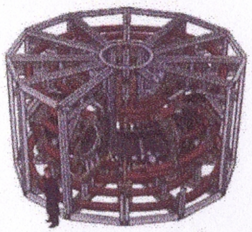
3-D coils

Tokamak



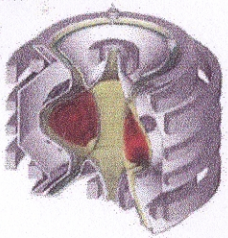
Planar coils, with nested sets

RFP

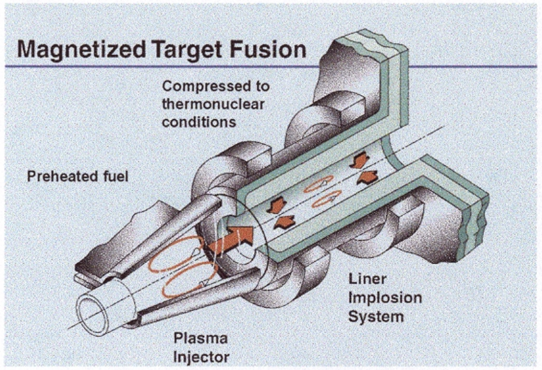


Low-field external coils

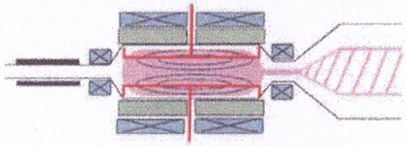
Spheromak



No toroidal coils



FRC



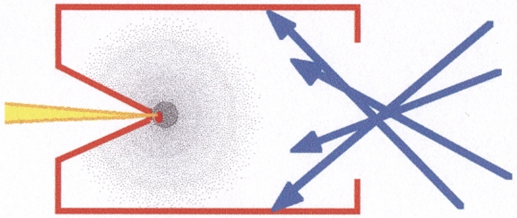
No toroidal field

But will it hold heat?

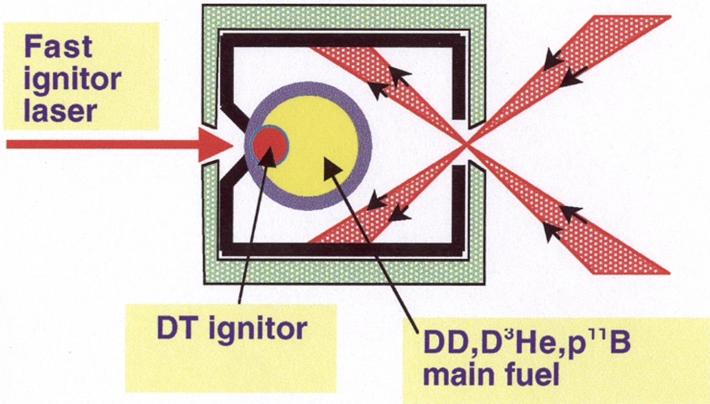
(T≥100,000,000°C)

In IFE, the Target Drives the Driver Requirements ⇒ Advanced Target Concepts?

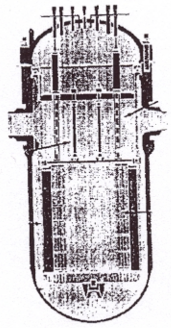
- **Fast ignition –**
  - Laser fast ignition – Point designs indicates gain ~350 for ~700kJ compression energy and ~100kJ fast ignitor
  - Cone focus geometries are under study
  - High-intensity laser-driven fast ions may be an alternative fast ignition option
  - In general, fast ignition may considerably relax present constraints on timing, symmetry, stability and target fabrication



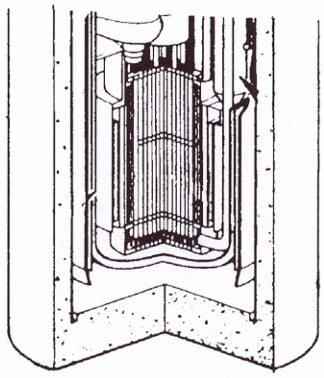
- **Advanced fuel targets –** Fast ignition may permit us to burn advanced fuels: D-D/D-^{3}He/p-^{11}B capsules with 1% DT ignitors. With 0-20% of the energy in fast neutrons, this might permit direct energy conversion of target output.



- **Can magnetic fields be employed?**
  - Z-pinches
  - Magnetized targets – pre-emplaced B-fields may aid hot-spot burn and suppress electron heat conduction

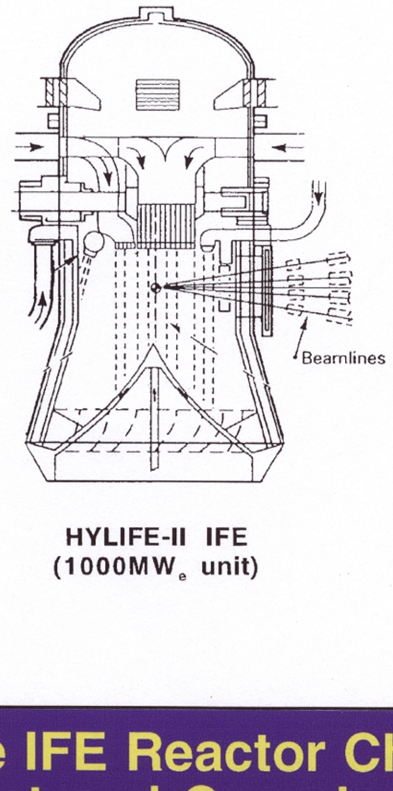


Westinghouse AP600
($600MW_e$ unit)

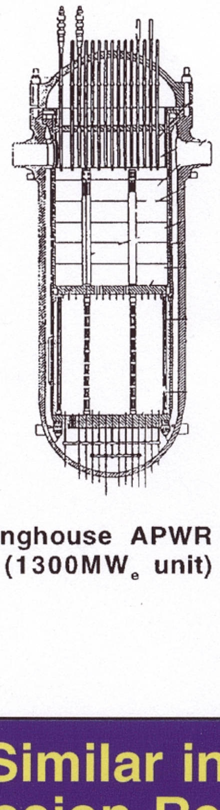


GE ALMR PRISM
($\sim 300MW_e$ unit)

0 1 2 3
m



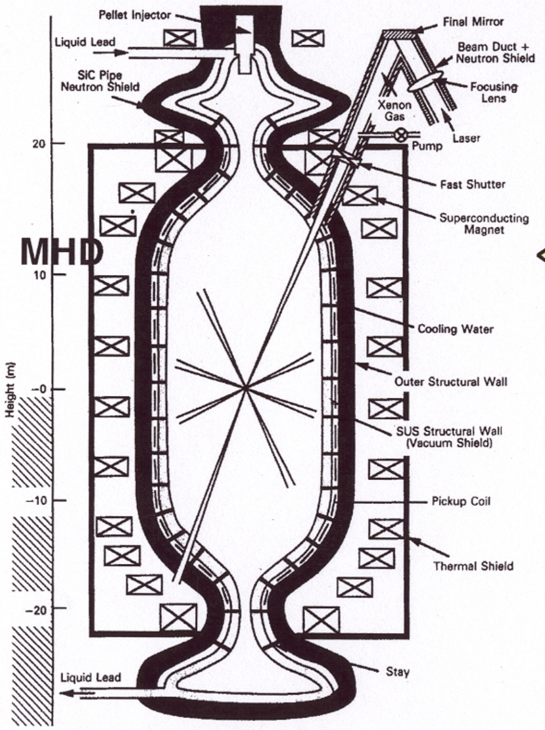
HYLIFE-II IFE
($1000MW_e$ unit)



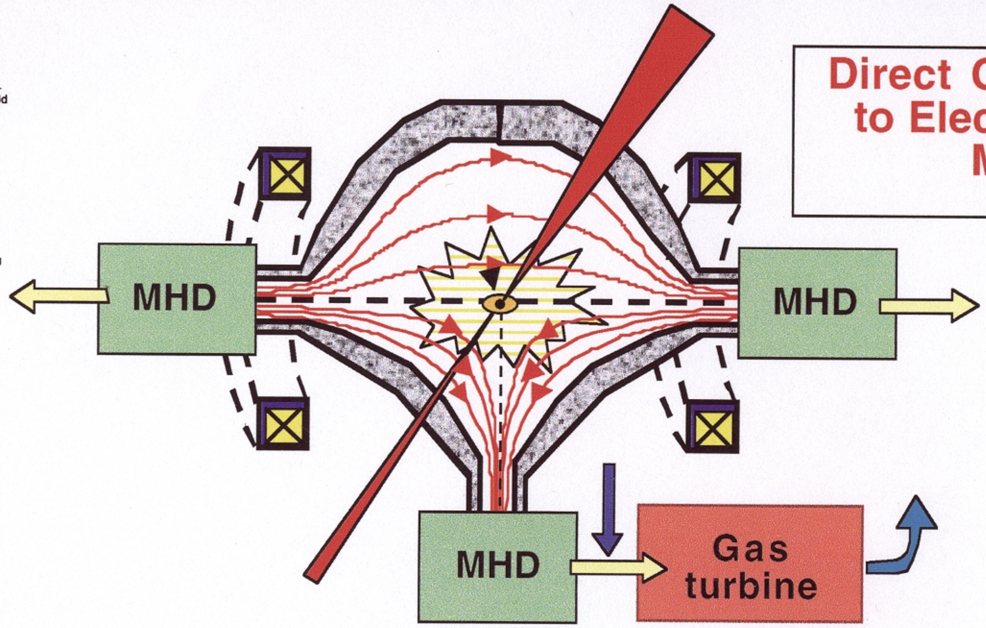
Westinghouse APWR 1300
($1300MW_e$ unit)

The IFE Reactor Chamber Is Similar in Size, Cost and Complexity to a Fission Reactor (to scale)

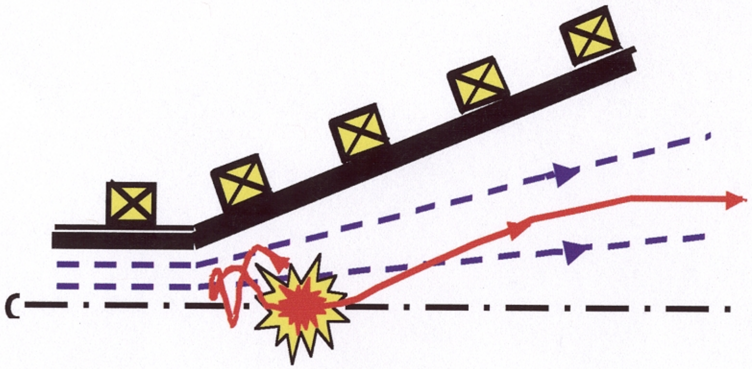
With Fusion Energy Appearing as Charged Particles (Plasma), We Could.......



Direct Conversion to Electricity via Flux Compression (*Mima et al*)



Direct Conversion to Electricity via MHD



Directed Thrust for Advanced Space Propulsion

⇒ **Can we do more with fusion energy than boil water for a steam cycle?**

1000MW$_e$ "MFE" REACTORS: THE IMPACT OF ULTIMATE PHYSICS

	Pulsed Inductive Tokamak(d) *ITER-like phys.(a)*	Steady-State Advanced Tokamak *Advanced, TPX or ARIES-like phys.(b)*	Neoclassical Tokamak *Neoclass τ_E, $\beta \leq 1$*	Magnetic Toroid *No τ_E, $\beta \leq 1$*	Ultimate Reactor(c) *No physics constraints*
Relative COE	**2.4 – 3.3**	**1.8**	**1.4**	**1.2**	**1.0**
Mass power density (kW$_e$/tn)	19 - 26	62	100	210	410
Reactor Plant Equip. fract.	**0.69– 0.75**	**0.63**	**0.55**	**0.43**	**0.34**
R_o (m)	9.0 – 11	5.7	4.2	3.8	1.6(c)
A	3.7 – 4.9	3.5	3.5	6.7	1.0*
I (MA)	18 – 15	11	8.0	N/A	N/A
B (T)	6.3 – 7.3	5.9	4.5	2.8	N/A
q_{95}	3.0* – 3.0*	4.0*	3.0*	N/A	N/A
P_{aux} (MW)	0 – 0	104	0	N/A	N/A
B.S. fract.	0.26 – 0.31	0.71	1.0*	N/A	N/A
Confinement H used	2.0* – 2.0*	2.72	N/A [5.2(f)]	N/A	N/A
Troy. Coef. β_N used	2.5* – 3.0* (d)	6*	N/A [10(f)]	N/A	N/A
β (%)	0.029 – 0.023	0.069	0.15	1.0*	N/A
Neut. wall load (MW/m^2)	1.6 – 1.2	3.5	5.9	12	13
Burn pulse length(hr)	1 – 10(d)	S. State	S. State	S. State	S. State

* -- Parameter at constraint bound or fixed. (a) Modest physics ($H \leq 2$, range reflects sensitivity to $\beta_N \leq 2.5$ - 3, and 1 – 10hr burn).
(b) Advanced physics ($H \leq 4$, $\beta_N \leq 6$, s-state) expected from sucessful TPX program. (c) Can be equally considered point source plasma with a sphericall FW radius at 3.75 + 0.15(s.o) = 3.9m to keep optimum neut. wall load at ~13MW/m^2 (optimum due to from blanket changeoput costs).Note this is also the ultimate ICF reactor (∞–rep rate). (d) Cases shown for inductive burn times in the range 1 – 10hr. The ARIES/PULSAR team (Sept 93) suggest optimum pulse length is ~3hr , implying~70,000 pulse fatigue cycles at end-of-life. A 10hr pulse length machine accrues ~20,000 pulse fatigue cycles. (f) H or β_N not constrained here but can be backed out from the solution point from other design variables.

Fusion Energy Beats Advanced Fission in Five Critical Areas.

⇒ Advanced Physics Solutions Must be Sought for the Remaining Areas

Fusion -v- Advanced Fission	
Safety and Environment	
Waste Disposal	
Non-Proliferation	
Fuel Cycle	
Advanced energy conversion potential	
Capital Cost	?
Complexity and Reliability	?
Development Path	?
Unit Size	?